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Baryogenesis through axion domain wall

S.N. Nayak and U.A.Yajnik

Physics Department, Indian Institute of Technology Bombay, Mumbai- 400076, India

Abstract

Generic axion models give rise to axion domain walls in the early Universe and they have to disappear not to overclose the universe, thus limiting the nature of discrete symmetry allowed in these type of models. Through QCD sphalerons, net chiral charge can be created by these collapsing walls which in turn can result the observed baryon assymetry.

nayaks@phy.iitb.ernet.in
yajnik@phy.iitb.ernet.in

The explanation of observed baryon asymmetry of the universe is still a hunting problem in the realm of cosmology and particle physics, thus generating lots of diverse ideas and activity. The earlier scenario to produce the asymmetry via the decay of heavy gauge bosons and scalar [1] in GUTS cannot survive the sphaleron wash out at the electroweak scale, unless B-L is an exact symmetry [2]. The scenario of electroweak baryogenesis through sphaleron transition also runs into problem because of inadequete CP violation in Higgs sector and more importantly, it is not clear that the electroweak phase transition is strongly first order to realise the out of equilibrium condition through bubble dynamics. In this background it was suggested to generate baryon asymmetry through topological defects (the remnants of some earlier symmetry breaking) at the electroweak scale [3]. In this scenario the baryogenesis takes place inside the core of the defects where the sphaleron transition takes place. Here we discuss the issue in the context of axion domain wall and show that we can produce sufficient amount of baryons at the scale much below the weak scale. Similar situation has been considered recently by Brandenberger et al [4].

Many axion models [5] also have discrete Z(N) symmetry which is spontaneously broken at $T = \Lambda_{QCD}$. This is generic for any axion models where the Pecci-Quinn symmetry $U_{PQ}(1)$ is broken only by QCD gluon anomaly. In the above N is the number of quark flavours that rotate under $U_{PQ}(1)$. Because of this discrete symmetry, there exist N degenerate and distinct CP conserving minima of the axion potential which is of the form

$$V(a) = {m_a}^2 (v_{PQ}/N)^2 [1 - f(aN/v_{PQ})], \tag{1}$$

where f is a periodic function of period 2π and v_{PQ} is the Pecci-Quinn scale. These disconnected and degenerate vacuum states gives rise to axion domain walls at $T = \Lambda_{QCD}$, when the discrete symmetry is spontaneously broken. The resulting domain walls have thickness $\Delta = m_a^{-1}$ and surface energy density $\eta = m_a {v^2}_{PQ}$, where m_a is the mass of axion.

These domain walls are disastrous cosmologically [6] and has to disappear so that they do not over close the universe, unless N=1. One way to achieve this is to introduce a soft breaking term of the form $\mu^3 \Phi$ [7]. Here we are considering DFSZ axion model and Φ is the singlet under standard gauge group [8]. This would produce an effective value of θ_{QCD} of order $\mu^3/{m_a}^2 v_{PQ}$. For this to be consistent with the upper limit on the electric dipole moment

of neutron we get

$$\mu^3 \leq 10^{-9} \frac{{f_\pi}^2 {m_\pi}^2}{v_{PQ}}. \tag{2}$$

This soft breaking term would produce a shift in energy density among the degenerate vacuum, hence a pressure towards the domain with highest vacuum energy leading to annihilation of walls. It is also possible that the domain walls created may not survive the QCD phase transition since $Z(N)$ symmetry may be dynamically broken.

In this letter we argue that even for the brief period that they exist they can produce sufficient amount of baryons. The important ingredient that goes in to our argument is the existence of the sphaleron like configuration in QCD and the rate of this topological transition is given by [9]

$$\Gamma_S = \kappa {\alpha_s}^4 T^4. \tag{3}$$

In the above α_s is the strong coupling constant and the proportionality constant κ can be of the order thousand [10]. This is the transition rate over the potential energy barrier separating vacua of different Chern-Simons number. But unlike the electoweak case where the sphaleron transition is the source of baryon number violation; the QCD sphaleron does not induce any baryon number violation since it has only parity conserving vector couplings. So as it is, this scenario will create some chiral charge separation mechanism. Baryogenesis will be achieved if additionally we have a nonvanishing chemical potential induced by other mechanism. For instance it could be a background field effect as in spontaneous baryogenesis scenario and its variants [11, 12].

The CP violating phase that is needed for baryogensis is nothing but the strong CP violating parameter θ_{QCD} which need not be zero at high temperature. The value of θ has to be decided by some stocastic process in a given horizon volume. The model we are discussing where the domain wall has to disapear due to the explicit soft breaking term has an effective θ that is consistent with above experimental constraint and also ensures that the walls do not overclose the universe [6]. We take the CP violating phase to be of order 10^{-10}.

The final ingredient for the baryogensis is the departure from thermal equlibrium. In our scenario this is automatically achieved when the walls annihilate due to difference in vacuum energy. The situation is similar to the model independent pictures of defect mediated baryogenesis. Whereas mere

translational motion or long lived defects cannot induce any net assymmetry, collapse and mutual annihilation can lead to creation of net assymmetry [3]. Let V_{BG} be the effective three dimensional volume in which the time irreversible processes occur during the disappearance of walls. Then the net baryon number density is then given by

$$\Delta n_B = \frac{1}{V} \frac{\Gamma_S}{T} V_{BG} \Delta\theta, \tag{4}$$

with V as the total volume.

As discussed earlier, the above formula needs to be supplemented by the contribution from a mechanism that converts the net chiral charge into baryonic charge. For example, one can consider an extra factor m_f/T with m_f as the fermion mass [12], in evaluating the baryon number density. In the baryogenesis scenario where electroweak sphaleron transitions takes place in the core of topological defects, this factor turns out to be order one. In our case this factor can enhance the rate of baryon production since the temperature we are interested is of QCD scale. But at present we are not considering this factor, as we are presenting our picture in a qualitative way and one has to see whether it enters in our calculation or not. Then the baryon to entropy ratio in volume V is

$$\frac{\Delta n_B}{s} = {g^*}^{-1} {\alpha_s}^4 \Delta\theta \frac{V_{BG}}{V}. \tag{5}$$

To evaluate the volume suppression factor, let us take the average separation of the domain walls as $\xi(t)$, which from kibble mechanism is

$$\xi(t) = {T_c}^{-1}, \tag{6}$$

where T_c is the temperature where Z(N) symmetry is spontaneously broken and is equal to $(m_a v_{PQ})^{1/2}$. Then the volume occupied by the domain walls in a horizon size $d_H(t)$ is

$$V_{BG} = \xi(t)^2 {m_a}^{-1} (\frac{d_{H(t)}}{\xi(t)})^3. \tag{7}$$

The last factor is the number of domains in the horizon volume. With this the volume suppression factor turns out to be

$$\frac{V_{BG}}{V} = (m_\pi f_\pi)^{1/2}/m_a. \tag{8}$$

In the above we have used $T_c = (m_a v_{PQ})^{1/2} = (f_\pi m_\pi)^{1/2}$. Since at QCD scale the pion mass can go to zero the above volume suppression factor can be of order unity for suitable value of the axion mass. This aspect of the problem requires detailed calculation in the specific axion model. But qualitatively, the thickness of the axion wall goes inversly proportional to the axion mass. The mass of the axion due to instanton effect at QCD scale is [13]

$$m_a(T) = 0.1 m_a(T=0)(\Lambda_{QCD}/T)^{3.7}. \tag{9}$$

So it is possible that at temperature just around QCD scale the thickness of the wall is only a few order of magnitude smaller than the horizon size and V_{BG}/V need not be a serious suppression factor.

Another crucial criteria that our picture satisfies, is the fitting of QCD sphaleron inside the axion domain wall, hence requiring no modification in the bulk value of Γ_S. The size of QCD sphaleron will be of order $\Lambda^{-1}{}_{QCD}$ which is smaller than the wall thickness that is ${m_a}^{-1}$ for allowed value of axion mass. So with κ of order thousand, the CP violating phase of the order 10^{-10} and g_* is of the order 10 we can produce sufficient amount of baryons at the QCD scale.

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